

Spin Dependent Parton Distributions in a Bound Nucleon

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Abstract

The determination of the spin distribution functions for the neutron requires an understanding of the changes induced by a nuclear medium. We present the first estimates of the changes induced in the spin-dependent, valence parton distributions of the proton and neutron bound in ^3He and ^6Li . For ^3He the result is quite reassuring, in that the off-shell correction to g_{1n} is very small. On the other hand, in ^6Li the corrections to the spin distributions in the bound proton are sufficiently large that they should be taken into account if one aims for a precision of better than 10%. We provide a simple parametrization of the off-shell changes in the valence spin distributions of ^3He and ^6Li , which can be used with any conventional estimate of nuclear binding and Fermi motion corrections.

There is considerable interest in deriving the corrections to the parton distributions of bound nucleons in order to finally understand the nuclear EMC effect [1, 2]. However, from the practical point of view there is a more pressing need. In the light of the activity associated with the violation of the Ellis-Jaffe sum rule [3], also observed first by the European Muon Collaboration (the “EMC spin effect”) [4], there has been a concentrated drive to determine g_{1n} in order to test the Bjorken sum rule [5]. This has led to a tremendous increase in our knowledge of the proton and neutron spin structure, both theoretically and experimentally [6]–[11]. On the other hand, all of the information about the neutron comes from nuclear targets – so far D, ^3He and most recently ^6Li . It is therefore imperative to have control over the corrections to the quark distributions for a bound nucleon.

For the deuteron the nuclear complications are sufficiently well understood that there have been several studies of the corrections to the neutron spin distributions extracted from D data [12]. In this case it seems that the off-shell corrections are under control, at least for

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$x \leq 0.7$. However, when it comes to heavier nuclei, such as ^3He , ^6Li and ^{15}N , the nuclear structure corrections may be of much more practical importance. Apart from this theoretical motivation, there is already some hint from recent experiments that nuclear corrections to nucleon properties may be significant in He. For example, recent studies of the neutron charge form factor in ^3He [13] suggest a possible difference between the measurement in D and ^3He [14].

In order to estimate the nuclear corrections to the parton distributions in nuclei such as these, at least at the present time when it is impossible to make a complete QCD based calculation, we need two ingredients. First, we need a model for the nucleon from which we can calculate free nucleon parton distributions that are in reasonable agreement with experimental data. Second, we need a theory based on the same quark model which can reproduce the essential features of the structure of the nucleus of interest.

We consider first the issue of calculating the parton distributions corresponding to a particular quark model. There is a long history of studies of this kind, beginning with the work of Le Yaouanc *et al.* [15], Jaffe [16] and Parisi and Petronzio [17] in the mid-70's. The basic idea is to connect the twist-2 parton distributions at a low scale with a valence dominated quark model – an idea exploited very successfully at the phenomenological level by Glück *et al.* [18]. A major problem with early quark model calculations, namely poor support, was solved about 10 years ago by formulating the problem in such a way that energy-momentum conservation was guaranteed *before* any approximation was made [19]. Using that technique it has been shown that, provided one allows for the hyperfine mass splitting between the $S=0$ and $S=1$ spectator pairs, the MIT bag model can give quite a good quantitative description of the observed valence parton distributions [20, 21].

The second essential ingredient has only been obtained quite recently. The quark meson coupling model (QMC), which is based on explicit quark degrees of freedom, is ideally suited for this purpose [22]–[27]. In its simplest form it is also based on the MIT bag model, with the interactions between different nucleons described by the exchange of scalar and vector mesons in mean field approximation. It has proven successful in reproducing the saturation properties of nuclear matter as well as the binding energies and charge densities of finite, closed shell nuclei. From the practical point of view, one of the most attractive features of the model is that it is not significantly more complicated than Quantum Hadrodynamics (QHD) [28] – even though the quark substructure of hadrons is explicitly implemented. A detailed description of the Lagrangian density, and the mean-field equations of motion needed to describe a finite nucleus, is given in Refs. [23, 24, 25].

Let us briefly outline some key features of QMC needed in the present calculation. For a bag centred at position \vec{r} in a nucleus (with the coordinate origin taken at the center of the nucleus), the Dirac equations for the quarks in the nucleon bag are given by [23, 24]

$$\left[i\gamma \cdot \partial_x - (m_q - V_\sigma(\vec{r})) - \gamma^0 \left(V_\omega(\vec{r}) \pm \frac{1}{2} V_\rho(\vec{r}) \right) \right] \begin{pmatrix} \psi_u(x) \\ \psi_d(x) \end{pmatrix} = 0 \quad (1)$$

The mean-field potentials at the centre of the bag are defined by $V_\sigma(\vec{r}) = g_\sigma^q \sigma(\vec{r})$, $V_\omega(\vec{r}) = g_\omega^q \omega(\vec{r})$, and $V_\rho(\vec{r}) = g_\rho^q b(\vec{r})$, with g_σ^q , g_ω^q and g_ρ^q being, respectively, the corresponding quark and meson-field coupling constants. (Note that we have neglected the variation of the scalar and vector mean-fields inside the nucleon bag due to its finite size [23].) For ^3He , which is too light for a simple shell model description, we use the empirical density distributions [29] and calculate mean-field potentials in the nucleus using local density approximation. However, for ^6Li we calculate the mean-field potentials and proton and neutron density distributions in the QMC model self-consistently, by solving Eqs. (23) – (30) of Ref. [24].

The effect of the mean field potentials on the internal structure of the nucleon can be totally absorbed into the normalization constant, the quark eigenenergy, a small change in the bag radius compared with free space and the relative renormalization of the lower component of the Dirac spinor:

$$\psi_q(\vec{r}', t) = N e^{-iE_q t/R} \begin{pmatrix} j_0(xr'/R) \\ i\beta \vec{\sigma} \cdot \hat{r} j_1(xr'/R) \end{pmatrix} \frac{\chi_s}{\sqrt{4\pi}}, \quad (2)$$

where r' is the quark coordinate in the bag and

$$E_q = \Omega + R(V_\omega(\vec{r}) \pm \frac{1}{2}V_\rho(\vec{r})) \quad \text{for} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \text{quarks}, \quad (3)$$

$$N^{-2} = 2R^3 j_0^2(x) [\Omega(\Omega - 1) + Rm_q^*/2]/x^2, \quad (4)$$

$$\beta = \sqrt{(\Omega - Rm_q^*)/(\Omega + Rm_q^*)}, \quad (5)$$

$$\Omega = \sqrt{x^2 + (Rm_q^*)^2}, \quad m_q^* = m_q - g_\sigma^q \sigma(\vec{r}). \quad (6)$$

Once we have the quark wave functions in medium, we can calculate the corresponding parton distributions. All that are required are suitable modifications of the free space expressions, which we now summarise.

In the case where the proton is described by the MIT bag model with just three valence quarks in the 1s-state, the dominant contribution to the twist-2 quark distribution is given by [20]:

$$q_v(x) = \frac{M}{(2\pi)^3} \int d^3 p_n \frac{|\phi_2(\vec{p}_n)|^2}{|\phi_3(0)|^2} \delta(M(1-x) - p_n^+) |\tilde{\psi}_+(\vec{p}_n)|^2. \quad (7)$$

This contribution comes from the case where the spectators to the hard collision are two valence quarks, again in the 1s-state of the bag, which can form a scalar (total spin $S=0$) or a vector ($S=1$) system. The ϕ factors come from the Peierls-Yoccoz momentum projection which is used to build translationally invariant states. The integration is over the momentum of the diquark spectator system in the intermediate state, ψ_+ is the plus component of the quark wave function in momentum space, and in Eq.(7) and in what follows x is the standard Bjorken scaling variable. More details concerning Eq.(7) can be found in Ref. [20].

After integration over the transverse components of the momentum of the diquark pair, we have:

$$q_v(x) = \frac{M}{(2\pi)^2} \int_{\frac{M^2(1-x)^2 - M_n^2}{2M(1-x)}}^{\infty} dp_n \frac{|\phi_2(\vec{p}_n)|^2}{|\phi_3(0)|^2} |\tilde{\psi}_+(\vec{p}_n)|^2. \quad (8)$$

In this paper, we will be working with the bag model wave function for a massless quark, which is given by Eq.(2) with $V_\sigma = V_\omega = V_\rho = 0$ for the free space case. In its simplest form, the bag calculation has just a few free parameters: the bag radius (for a free nucleon), the scalar (M_s) and vector (M_v) diquark masses, and the starting scale, μ , for the QCD evolution (at which the bag model is supposed to best represent the non-perturbative structure of the nucleon). They are fixed by fitting the valence distribution to the respective existing parametrizations for the experimental data. This procedure has been quite successful in the past [20, 21], showing that the bag model is able to describe not only the unpolarized valence sector, but also has very good predictive power for the polarized sector [30]. In this work, we use $\mu^2 = 0.1 \text{ GeV}^2$, $R = 0.8 \text{ fm}$, $M_s = 700 \text{ MeV}$ and $M_v = 900 \text{ MeV}$, which are the values for the parameters which give a good fit to the MRSA parametrization of the valence distribution.

In calculating the twist-2 parton distributions in the bound nucleon one must omit any interaction between the struck quark and the nuclear medium. However, the bound nucleon

itself and the pair of spectator valence quarks in the struck nucleon still feel the mean scalar and vector potentials [31]. That is, in-medium the σ and ω coupling at the quark level change the mass and energy of the nucleon and the zero component of the momentum of the intermediate state in the following way:

$$\begin{aligned} M &\rightarrow M^* + 3V_\omega^q \\ p_n^0 &\rightarrow (p_n^0)^* + 2V_\omega^q. \end{aligned} \quad (9)$$

Note that the Bjorken variable, x , is defined in terms of the free nucleon mass, M , so that Mx is actually mass independent. This is an important observation as it directly effects the integration region.

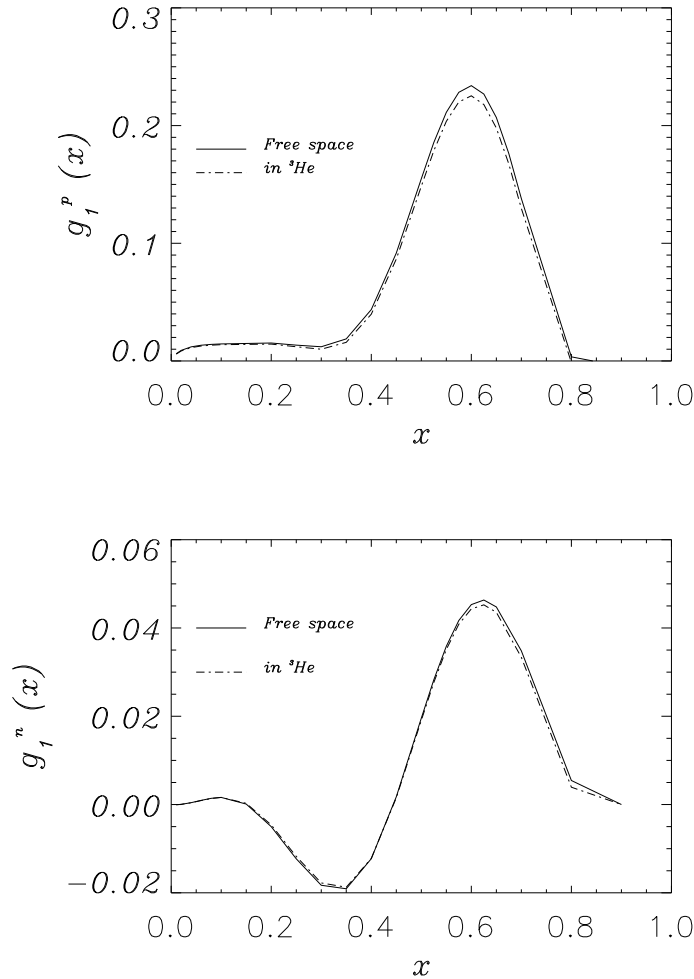


Figure 1: The valence quark contributions to the proton and neutron structure functions calculated in free space using Eq. (8) and in ^3He using Eq. (14).

Incorporating these changes, the quark distribution for a nucleon at rest in the medium is given by:

$$q_v^{(\tilde{N})}(x) = \frac{M\tilde{y}}{(2\pi)^2} \int_{\frac{(M^*+V_\omega^q-Mx)^2-M_n^{*2}}{2(M^*+V_\omega^q-Mx)}}^\infty dp_n \frac{|\phi_2(\vec{p}_n)|^2}{|\phi_3(0)|^2} |\tilde{\psi}_+(\vec{p}_n)|^2, \quad (10)$$

with

$$\tilde{y} \equiv \frac{M^* + 3V_\omega}{M} = \frac{p_{\tilde{N}}^0}{M}. \quad (11)$$

There is a second important observation to be made regarding the in-medium calculations. This concerns the ρ meson coupling to the quarks [23, 24, 28]. In this case, Eqs.(9) are modified to $M \rightarrow M^* + 3V_\omega^q + \frac{1}{2}\tau_3^N V_\rho^N$ and $p_n^0 \rightarrow (p_n^0)^* + 2V_\omega^q + \sum_{j=1}^2 \frac{1}{2}\tau_3^q(j)V_\rho^q$, where τ_3 are the nucleon and quark isospin matrices and $V_\rho^N = V_\rho^q$ is the rho meson potential. We note that, with the inclusion of the ρ meson, these expressions imply different integration minima for the u and d quark distributions in the bound proton. Moreover, in a nucleus with $N \neq Z$, the valence distributions are no longer charge symmetric between the proton and the neutron, meaning that the substitutions $d_v^p(x) = u_v^n(x)$ and $u_v^p(x) = d_v^n(x)$ may be less accurate in-medium than in free space. This is a model independent phenomenon, and its origin, unlike the free space investigations of isospin breaking in the valence distributions [32], is not in the quark masses. In practice, the mean field potential V_ρ^q is quite a bit smaller than those associated with σ and ω and we shall drop it in this first investigation.

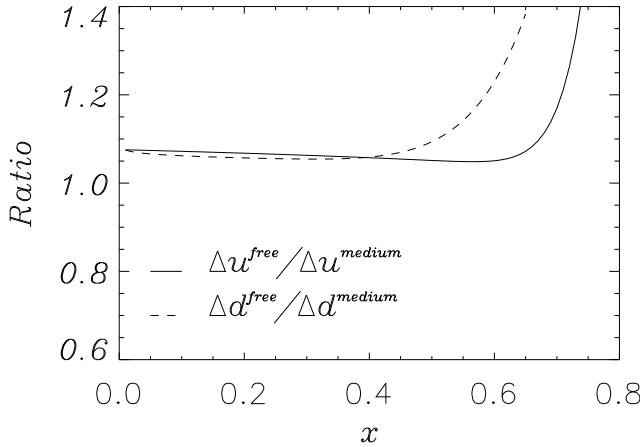


Figure 2: The ratio of free to ^3He polarized, valence quark distributions in the proton for the u and d quarks.

Although correct, Eq.(10) is not yet suitable for the in medium calculation for the following reason. When calculating the quark distributions in a nucleon, we express them as a function of x , which is a fraction of a chosen unit of momentum (in this case the mass of the proton, M). If we now want to calculate the quark distribution of a nucleon which itself has a certain momentum distribution inside a nucleus, then this quark distribution will be a function of the momentum fraction y carried by the nucleon. However, our Eq. (10) was derived for a nucleon with momentum $p_{\tilde{N}}^0 = M^* + 3V_\omega$. We therefore define a new valence quark momentum distribution:

$$q_{v/\tilde{N}}(x) = q_v^{(\tilde{N})}(\tilde{y}x). \quad (12)$$

For an arbitrary nucleus, we then have the following convolution formula for the nuclear valence distribution at leading twist [2, 33]:

$$q^{(A)}(x) = \int_x^A \frac{dy}{y} f_{N/A}(y) q_{v/\tilde{N}}\left(\frac{x}{y}\right). \quad (13)$$

where $f_{N/A}(y)$ is the usual momentum distribution function for the nucleons inside the nucleus[2, 33]. This choice ensures the valence quark number (Gross Llewellyn Smith) sum rule as well as the appropriate momentum sum rule. The distributions presented in this paper will be for $q_{v/\tilde{N}}(x)$ calculated through Eq.(12). We emphasise that Eq.(13) is the standard nuclear convolution, which accounts for the kinematic corrections associated with binding and Fermi motion, so the ratio $q_{v/\tilde{N}}(x)/q_v(x)$ is a measure of the genuine off-shell correction to the valence parton distribution. Our parametrizations for this ratio (see Eqs. (16) and (18) below) can therefore be used in conjunction with any conventional calculation of the nucleon momentum distribution, $f_{N/A}(y)$.

The quark distributions in medium are not only a function of x but also a function of the distance, r , from the centre of the nucleus. Hence we average the quark distributions over the nuclear density:

$$q_{v/\tilde{N}}(x) = \int d^3r q_{v/\tilde{N}}(x, r) \rho_{\tilde{N}}(r). \quad (14)$$

Note that as we have already specified the momentum of the bound nucleon, this averaging procedure amounts to a semi-classical approximation. It is an interesting challenge for future work to improve on this point. Here $\rho_{\tilde{N}}(r)$ is the probability density for the struck nucleon and $q_{v/\tilde{N}}(x, r)$ is the quark distribution calculated at the local nuclear density at \vec{r} for a bag with the effective mass, radius and so on given by the QMC equations. Eq. (14) is valid for ^3He , where the two protons and the neutron are in s-waves. However, ^6Li may be thought of as an α particle plus a neutron-proton pair, each one in a p-state. It is this pair, with deuteron quantum numbers, which gives the spin of the ^6Li nucleus. Thus, when calculating the ^6Li spin structure function we average only over the proton and neutron p-state densities (calculated with the help of the QMC equations). In the particular case of the proton in ^6Li , $\rho_{\tilde{N}}$ is simply the density of protons in the p-state. For g_1^n it is the neutron density in the p-state. In actual calculations, the structure function for the bound nucleon was calculated over a grid of values of r , with interval 0.04 fm , running from $r = 0$ to $r = 4 \text{ fm}$ for ^3He , and from $r = 0$ to $r = 12 \text{ fm}$ for ^6Li .

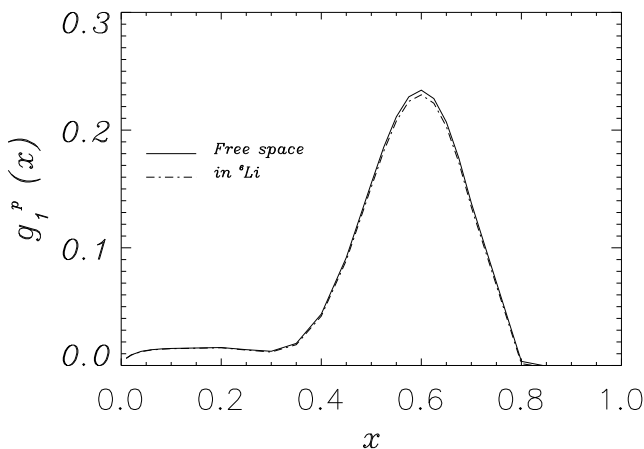


Figure 3: The valence quark contribution to the proton spin structure function calculated in free space and in ^6Li .

For the ^3He case, we use [29] $\rho_{^3\text{He}}(r) = 0.149 \exp[-0.4244 r^2]$ in Eq. (14) to calculate the corresponding distributions. The results are shown in Fig.1, where we show the structure

function, $g_1(x)$, for a free proton (neutron) in comparison with that for a proton (neutron) bound in ${}^3\text{He}$. Note that we have not carried out the convolution (c.f. Eq.(13)) needed to include conventional binding and Fermi motion effects, so the difference between the two curves is solely a measure of the off-shell corrections for the bound nucleon. We see that these corrections are not significant in comparison with the current experimental errors. This is an important result when we remember that ${}^3\text{He}$ has been chosen because, from the point of view of its spin structure function, it is assumed to be a pure neutron target. Our result vindicates this view, since we get almost no correction for the neutron spin structure function. (On the other hand, our result says nothing new about the standard nuclear corrections associated with the kinematics of binding and Fermi motion, nor about the nuclear structure corrections associated with wave function components other than the neutron with a pair of spectator protons in the 1S_0 state. Those corrections can be estimated from standard nuclear structure calculations [2, 33].)

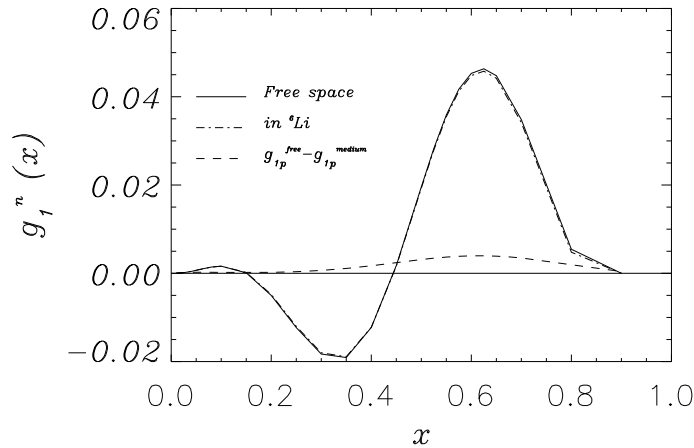


Figure 4: The valence quark contribution to the neutron spin structure function calculated in free space and in ${}^6\text{Li}$. Also shown is the difference $g_{1p}^{\text{free}}(x) - g_{1p}^{\text{medium}}(x)$, which is relevant for the extraction of $g_{1n}(x)$ from the measured value of $g_1^{\text{Li}}(x)$.

In Fig. 2 we show the ratios of the free to the bound polarized u and d quark, valence distributions. The in medium corrections are practically the same for the u and d distributions in the whole valence region, up to $x \approx 0.45$. In the large x region, the d distribution in ${}^3\text{He}$ is suppressed relative to its free counterpart at a faster rate than the u distribution. The calculated ratio of the polarized, valence quark distributions for the proton in free space to that in medium can be parametrized in the following way:

$$\frac{\Delta q_v(x)}{\Delta q_{v/\tilde{N}}(x)} = a_q x^{b_q} + c_q x^{d_q} (1-x)^{e_q}, \quad (15)$$

with the parameters:

$$\begin{aligned} a_u &= 118.41 & , & & a_d &= 8.964 \\ b_u &= 18.97 & , & & b_d &= 7.5848 \\ c_u &= 1.0758 & , & & c_d &= 1.0515 \\ d_u &= 0 & , & & d_d &= -0.0048 \\ e_u &= 0.0335 & , & & e_d &= 0.01086. \end{aligned} \quad (16)$$

A similar procedure is used to calculate the in-medium corrections to the proton and neutron spin structure function in a ${}^6\text{Li}$ target – see Figs. 3 and 4. The main differences with respect to the ${}^3\text{He}$ case are that the nuclear density in ${}^6\text{Li}$ is calculated self-consistently in QMC, as explained in the introduction, and the average is over the proton and neutron p-states only. The ratio of the free to bound, polarized valence quark distributions can be parametrized as:

$$\frac{\Delta q_v(x)}{\Delta q_{v/\tilde{N}}(x)} = a_q + b_q x^{0.5} + c_q x + d_q x^{1.5} + e_q x^2 + f_q x^{2.5} + g_q x^3, \quad (17)$$

with

$$\begin{aligned} a_u &= 1.1267 & , & & a_d &= 1.0904 \\ b_u &= -2.2012 & , & & b_d &= -1.4308 \\ c_u &= 17.3645 & , & & c_d &= 12.0596 \\ d_u &= -66.6193 & , & & d_d &= -50.0592 \\ e_u &= 132.6824 & , & & e_d &= 107.9883 \\ f_u &= -131.2261 & , & & f_d &= -116.1088 \\ g_u &= 50.7843 & , & & g_d &= 49.2399. \end{aligned} \quad (18)$$

As in the case of ${}^3\text{He}$, the off-shell corrections to be made to the deconvoluted nucleon spin structure functions are not large. However, in order to extract $g_1^n(x, Q^2)$ from a ${}^6\text{Li}$ target, one has to subtract $g_1^p(x, Q^2)$ from the measured value of $g_1^{6\text{Li}}$. In this case, one can see from Fig. 4 that the use of the free $g_1^p(x, Q^2)$ would induce some underestimate of $g_1^n(x, Q^2)$ over the region $0.4 < x < 0.8$. The off-shell corrections to the proton spin structure functions are as much as 6-8% of g_1^n itself. They will therefore become important to the determination of $g_1^n(x, Q^2)$ when the experimental precision gets to this level.

Although the magnitude of the off-shell corrections calculated here is model dependent, we believe that the ratios should be less sensitive to the details of the model. In this sense, the parametrizations for $\Delta q_v(x)/\Delta q_{v/\tilde{N}}(x)$ through Eqs. (15) - (18) are suitable for general use when making the nuclear deconvolution. We note also that we have verified that the ratios of the valence distributions presented here are approximately scale independent so that they can be safely used for Q^2 up to 10 GeV².

The results presented here are the first consistent calculations of off-shell corrections to the proton and neutron valence spin structure functions in nuclei heavier than the deuteron. By consistent we mean that the quark model used to calculate the parton distributions is the same model used to calculate the nuclear structure. All the parameters were fixed in order to reproduce data other than nuclear deep inelastic scattering and therefore the results shown here really are predictions. Most important, perhaps, is the fact that we have at our disposition a procedure where the off-shell corrections to the valence quark distributions can be systematically studied.

Overall, we have one main prediction together with one main confirmation. First, it is reassuring that one can indeed identify the measured spin structure function of ${}^3\text{He}$ with the neutron spin structure function, without significant off-shell corrections. Second, our work indicates that future experiments using ${}^6\text{Li}$ as a target, will need to take into account the in-medium corrections, of the type calculated here, when extracting $g_1^n(x)$.

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